PLATON –

Planning Process and Tool for Step-by-Step Conversion of the Conventional or Mixed Bus Fleet to a 100% Electric Bus Fleet

Deliverable 5.3: **Implementation and Tests**
Part of milestone M4
Main Work package WP 5.7 Tests

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Contents

1 Introduction

The deliverable presents the results of the project work carried out by consortium partners in the WP 5.7: Tests. It summarizes approaches which were developed in the course of the project in part one and amends with a vision to the application, in part three without prejudicing work in WP6 which is constrained by the situation with the demonstrators. Part two is detailing preconditions of the planned implementation.

In this task the final implementation and technical client tests were conducted. With these tests the correct functionality and interaction of the whole service chain (all integrated components as well as the web application) was evaluated. Complex tests according to the particular use cases with different scenarios were performed. The achieved results confirmed the functionality of the service chain and the seamless data exchange between the PLATON tool components which are described in the present deliverable

2 Type of implementations

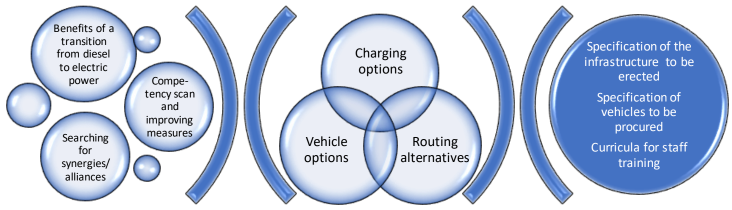
2.1 Structuring the approaches

The type of implementation is different, depending on the situation in which a public transport operator is found. In this chapter the potential cases are described. The cases might be located in the phasing of the transition as depicted in Figure 1. The phases start with the strategy development and end with the planning. The project contact to transport operators has shown that much work will be conducted by external entities.

- Bus producers calculate SOC for a specific bus/battery configuration for a particular application case
- Consultants do plan the erection and procurement of a bus line with opportunity charging and/or depot charging respectively
- Management of public transport operators are planning mid-term investment budgets for their fleet electrification project
- Municipal planners aim to localize potential charging facilities
- Public transport operators are due to develop electric vehicle schedule cycles in accordance with daily transport service tasks

Typical scenario cases are itemized in the following sections including the required data input, the expected reasoning or algorithm to find a solution and the supposed output of the scenario case.

Tools and Phasing of the Transition



	Strategy Development	Pre-Planning	Planning
General Recommendations	What variants are best, based on the starting position?		
Checklists	What competencies are needed?	Requirements fleet management based on telemetry?	
Tools with System Wide Scope	What are the benefits for the city?	What is the charging option with minimum cost? What route options should be considered?	What are the consequences of bus assignment variants? How costs will change over time? Validating electric grid stability
Route specific tools, also depending on actual conditions		What is a good order of routes to commence with? What time depending bus assignment scheme is optimal?	Assignment of bus types to routes Consequences of variable/fixed bus assignment

Figure 1 Investigation subjects for different planning stages of Environmentally Sustainable Transport (EST)

2.1.1 Preparing a demonstrator

Scenario:	A transport operator wishes to check the feasibility of the transition to battery electric buses for a given bus route.
Data input:	High accuracy tracking data is required for the description of route characteristics. It will be acquired by GPS data loggers with high time-space resolution.
Reasoning/Algorithm:	The on-line simulation of the bus propulsion and charging operations at http://simulation.publictransport.info developed for the PLATON project is recommended.
Data output:	State of Charge (SOC) time-space values over the input route and additional data

2.1.2 Validating a propulsion design

Scenario:	A bus manufacturer intends to test his concept with given data for a bus route. Alternatively, a transport operator wants to decide whether a certain propulsion and charging concept is suitable.
Data input:	Same as in 2.1.1, bus vehicle specifications have to be provided in addition
Reasoning/Algorithm:	Same as in 2.1.1
Data output:	Same as in 2.1.1

2.1.3 Benefit/Cost ratio transition

Scenario:	A transport operator may spend a certain amount of money for transiting part of the fleet and wants to know where to start.
Data input:	Same as in 2.1.1, additionally immission data
Reasoning/Algorithm:	Same as in 2.1.1 plus algorithms for determining benefit
Data output:	List of best suited routes

2.1.4 Tackling air quality problems

Scenario:	A municipal planner wants to mitigate air quality problems and needs information where the benefit to cost ratio of a transition is best.
Data input:	Bus characteristics, immission data, emission data existing buses
Reasoning/Algorithm:	Simulation of operation, model for calculation of emission
Data output:	List of best suited routes

2.1.5 Strategic approach

Scenario:	A municipal planner wants to know the best scenario for transition to electrification of the entire public bus network.
Data input:	Bus and charger characteristics, location power substations, medium voltage power grid layout
Reasoning/Algorithm:	Simulation of operation, calculation of TCO for different alternatives (possibly including in-motion charging)
Data output:	Scenario description as for example: Because of the high cost of batteries the shorter routes with longer dwells at terminal stations are preferred in the beginning, especially if the stations are located in the vicinity of tram power substations for example.

2.2 Environmental focus

2.2.1 Approach

In result of the PLATON project are provided recommendations and key technical, operational, economic, societal and ecological indicators for the transition process from conventional buses to fully electric buses. By application of the PLATON toolkit the public transport operators shall be enabled to analyze in detail how an electric bus system fits to the particular needs of the urban area of deployment. This analysis includes technical and operational conditions and economic and ecological costs of the deployment case.

Therefore, ecological models which considering the entire life cycle of energy storages including possibilities of recycling and mining of the raw materials as well as much more detailed air pollution models are considered. Basic services such as ecological assessment of the costs, among others, are provided by web services. For the purpose of evaluation, also the ecological impact has to be assessable.

In the following two approaches are investigated with regards to the environmental assessment. The first concentrates on toxic emissions, here mainly NO_X, and the second approach concentrates on climate effects, here mainly caused by CO_2.

2.2.2 Toxic emissions

Particular cities and metropolitan areas situated in valleys may having fewer air exchange with the surrounding countryside. These conurbations experience problems to meet the EU-regulated NO_x and PM immission limits. A major source for emissions is road traffic whereas other sources such as agricultural land tillage emitting soil dust increase particular matter concentration remarkably. The immissions having impact on a particular city district or area are furtherly regulated by national law such as in Germany the Bundes-Immissionsschutzgesetz (BImSchG).

Through electrification of bus vehicle propulsions, the PM immission is not reduced in general, in analogy to the reduction of emissions, because tyre abrasion takes place as well in battery electric vehicles. However, electric vehicles emit fewer particulate matter from abrasion of braking pads because braking energy is regenerated which causes additional deceleration. The typical electric powertrain of bus vehicles (like TM4) contains no transmission, therefore no emissions are caused in the powertrain.

The influence of velocity has to be taken into account only for speeds above 40 km/h. Tyre emissions are in the range from 2.5 to 10 µm [22]. The aerodynamic drag is depending on the product of frontal area A_q and drag coefficient c_w value and the square of the vehicle speed [20], which means that supercapacitors or power transfer equipment on the roof (like pantographs) increase aerodynamic drag.

Due to the aerosol layer being denser above the street level, underbody aerodynamics might also play a significant role. However, this might be only significant for higher bus velocities and PM re-suspension is absent when it rains. The effect even persists partly after the rain period [22]. The complexity of the emission model makes it difficult to evaluate the impact of exchanging diesel buses by battery electric buses. The primary emission NO (measured as NO_2) is a gas which is irritating the respiratory system [27]. Subsequently, the NO is oxidized into NO_2.

Data provision

For heavy duty vehicles, the regulations state a limit related to the fuel energy. This specific emission might be cumulated by using a specific driving cycle. In Figure 2 is shown the velocity profile of a bus cycle in the city of Braunschweig.

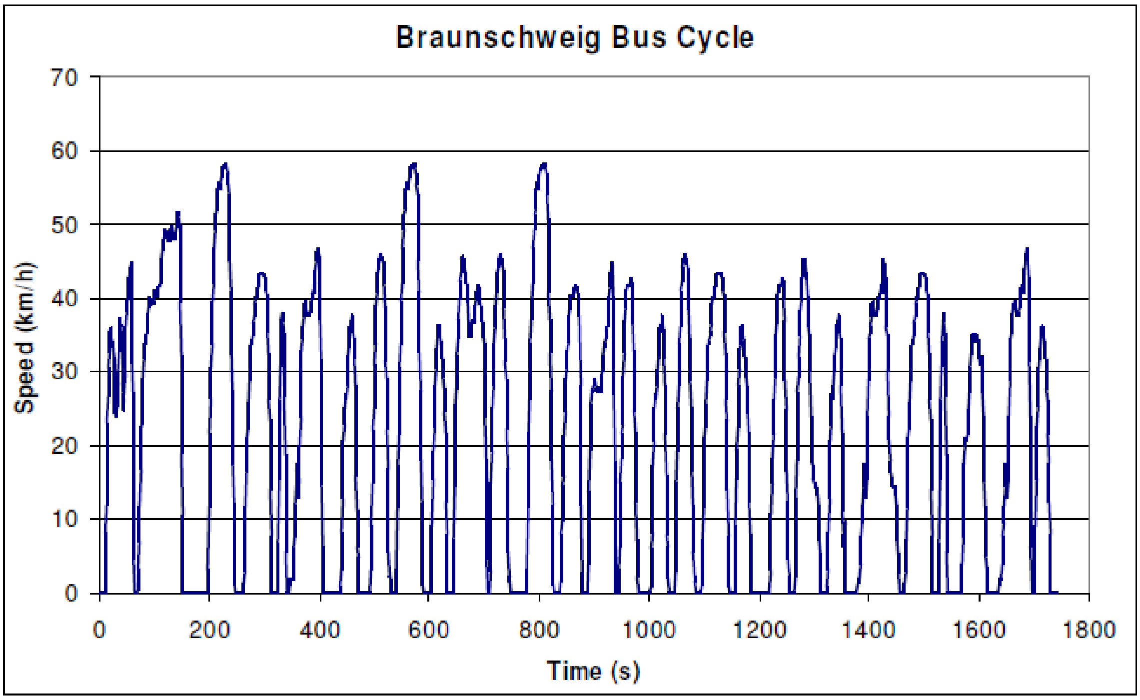


Figure 2 Speed vs. Time of the Braunschweig Bus Cycle (Nils-Olof Nylund, 2004) [27]

In Figure 3 is shown the EURO limits together with real world measurements in the Braunschweig bus cycle.

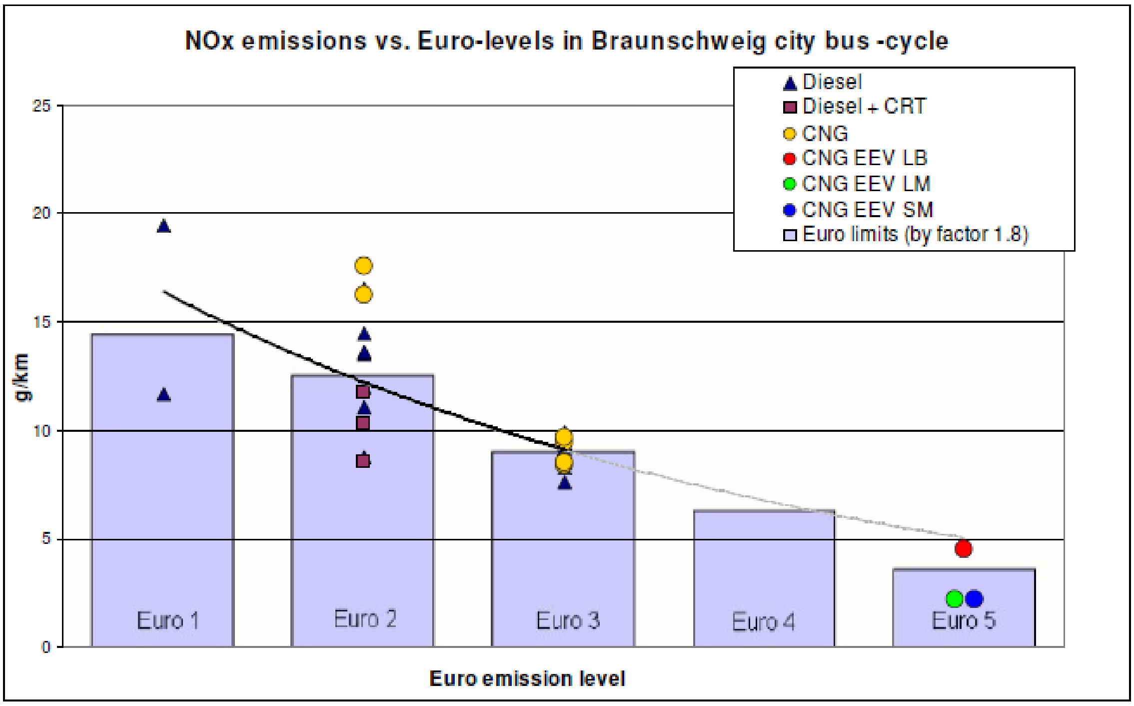


Figure 3 EURO emission levels and real-world measurements (Nils-Olof Nylund, 2004) [27]

On this basis even the emission difference, when exchanging older CNG vehicles, may be calculated. If the production of the batteries is taking place at other locations, the local immission level is not altered.

But this cumulative approach is not significant for NO_X - emissions which increase disproportionately with the power, when accelerating severely. In the Final report of the COST project 346, formulas were developed approaching the real emissions of heavy-duty vehicles. Figure 4 shows in an exemplary way the dependency of the NOx emissions from the average cycle speed. The depicted dependency indicates that driving at higher average speed with less acceleration and deceleration leads to lower $NO+NO_2$ emissions than at lower average speeds because of fast changing speeds causing more exhaust than constant low velocities.

A second dependency is on the ambient temperature. Here we only have data for light commercial vehicles. Indicating that EURO IV and V diesel engines emit 170% more NO_X, below 0°C (Matzer, et al., 2019) [24].

The calculations may be applied to real world velocity cycles. There are at least two bus cycles in which the real-world emissions are calculated, but this data is not usable for comparing bus routes having different speed/terrain profiles.

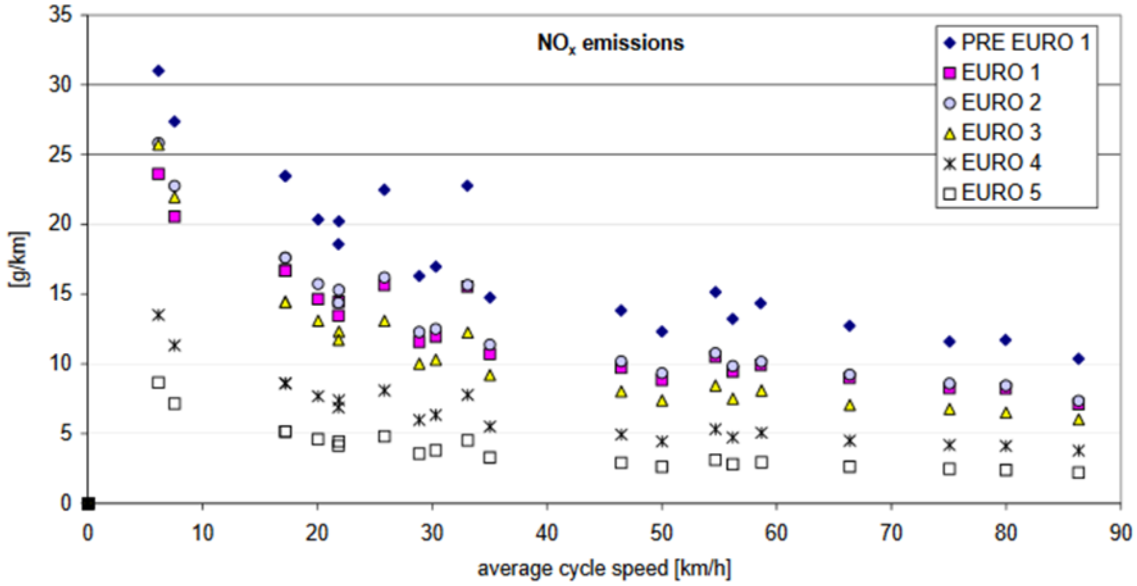


Figure 4 Speed dependency of NOx emissions calculated for heavy trucks 34 to 40 tons, 50% loaded, 0% road gradient (STURM & HAUSBERGER, 2009) [30]

Table 1 Average velocities for bus service types

Service type	Average velocity
City centre driving route	below 17 km/h,
Liaison and suburb routes	between 17 and 25 km/h.
Distant suburb routes	between 25 and 35 km/h
Town to town service	40 km/h

Those figures might not be applicable if the city center was adapted to cars, having fewer stop-n-go traffic or after having introduced bus lanes with a higher percentage. Thus, for comparing emissions in more detail a scheme shall be used which calculates the emissions based on the longitudinal movement. This model was developed in COST 346 [30], also like ARTEMIS a COST funded project, but focusing on emission from heavy duty vehicles. Alternatively, there are possibilities to deduct the cycle characteristics from the percentage of the stop time and take cycle emissions. Figure 5 shows the correlation between stop time and average speed.

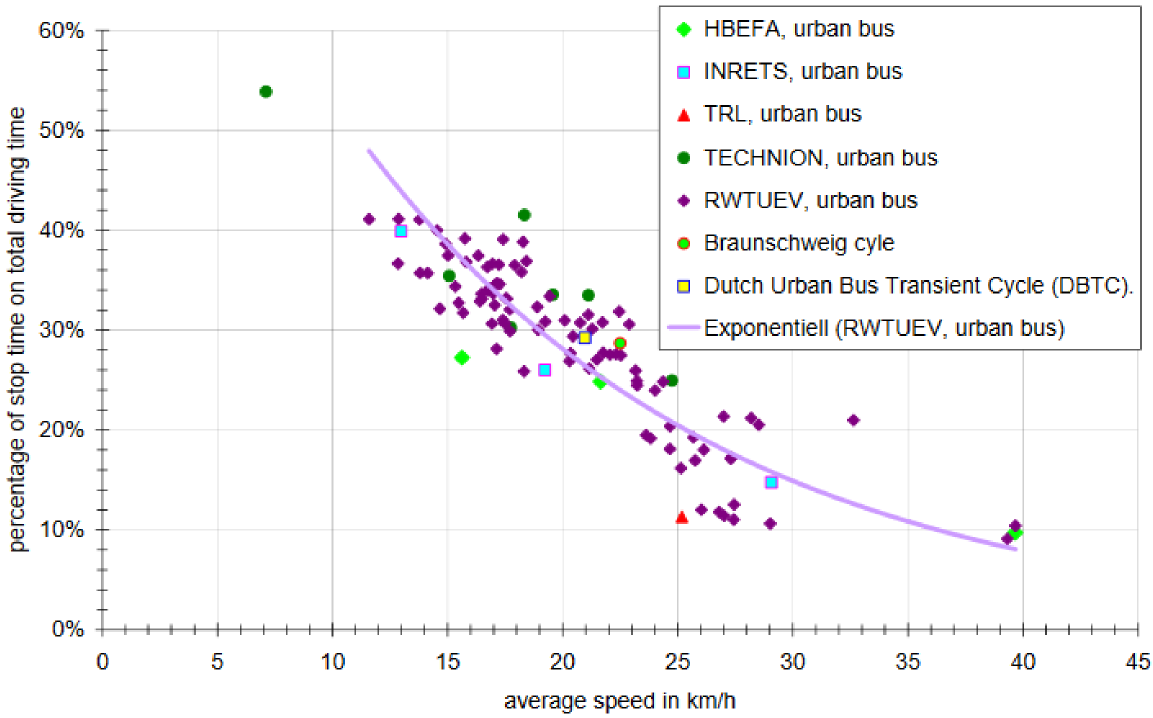


Figure 5 Average speed and percentage of stops for urban busses (STURM & HAUSBERGER, 2009) [30]

Calculation of environmental benefits (NO$_X$)

The emissions might be calculated based on distance, average velocity and distance, or based on the longitudinal speed profile. Average velocity might be derived from the type of the area the bus is passing. For determining bus lines/routes to be taken first - when transiting to battery electric bus fleets - it is necessary to differentiate the environmental benefits.

This aspect has two components:

- How far immissions might be reduced starting from values near or above immission limits
- What is the absolute reduction in emissions?

The proposed approach combines both items into one formula:

$$\Delta \mathrm{Env} = \sum (\Delta \mathrm{Emission} \cdot f_{\Delta \mathrm{Immission}}) \quad (1)$$

$\Delta\mathrm{Emission}$ is calculated using the most detailed method possible. So, if the average velocity or type of driving cycle is known this will be the input. If the longitudinal speed profile is known, then more detailed emissions may be calculated. Table 2 recaps the alternatives:

Table 2 Calculation method for emissions

Data available	Method
No speed nor route characteristics	fixed value g/km
Average route speed	fixed value g/km chosen for the average speed
Speed vs. time	Calculated value for the emissions

With regards to the data provision the following workflow shown in Figure 6 is visualized.

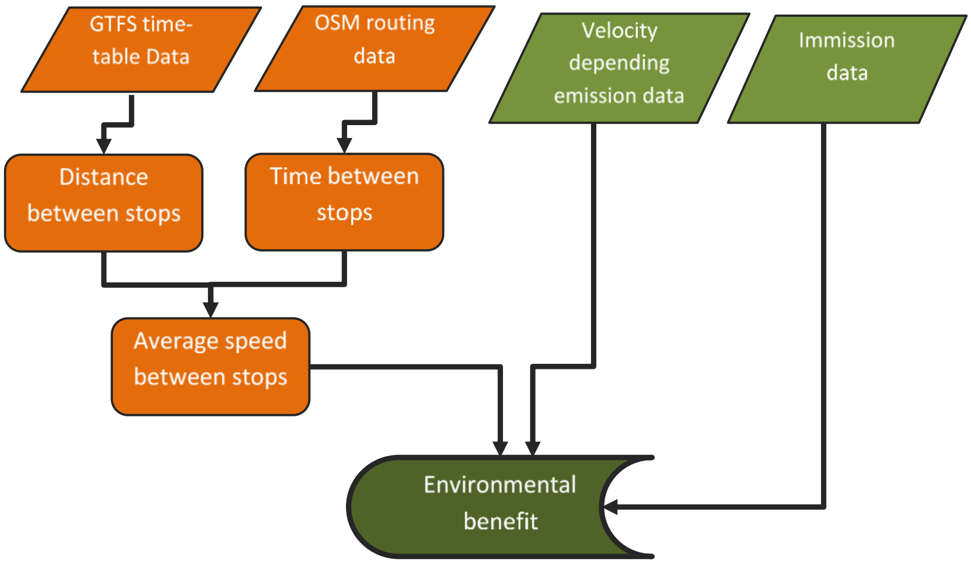


Figure 6 Workflow of environmental benefit calculation

In the calculations for Austrian cities a base value for the pollutants CO, HC, NO_X and PM may be assumed, as shown in Figure 7

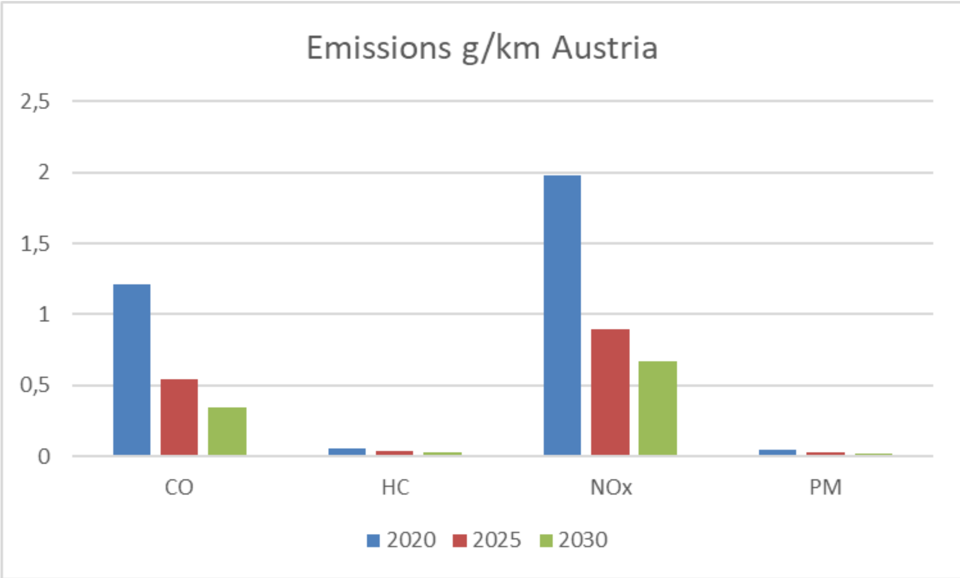


Figure 7 Future average emission factors for urban buses for Austria (Matzer, et al., 2019) [24]

The factor accounting for the influence of the difference in emission is a function of the existing actual immission.

The principal approach for weighting emission reduction is given in the following equation.

$$f_{\Delta Imm} = f(c_{Imm)}) \tag{2}$$

The function may have a linear dependency on yearly average emission level, or the daily average if there are peak days with elevated immission to be considered. The dependency may be also assumed as exponential or quadratic. Equation 3 shows an example for an exponential function for the weighting of the emission reduction.

$$f_{\Delta Imm} = e^{\frac{c_{Imm}}{c_{ImmLimit}}} \tag{3}$$

The contribution to the environmental benefit is therefore calculated for each stretch, taking into consideration the relative distance of the immission level and the absolute reduction of the emission, caused by all buses passing the stretch. So, stretches having high immission levels where many buses passing with high dynamic speed part will contribute more to the reduction of the problems caused by immissions.

It is possible to include a total for all emissions beside NO_X if they are weighted with the respective immission limits.

2.2.3 Charging technology assessment

In order to provide support for a profound decision making with respect to use of alternative technologies for propulsion they will be compared using a holistic approach in the following chapter.

Depot charging case

In the case of depot charging the buses are charged at least for 2-4 hours mostly overnight, mainly in the depot or at positions, where they are waiting to be dispatched. As type of energy storage presently the chemistries of Lithium-manganese-cobalt-oxide (NMC), Lithium-Titanate-oxide (LTO) and Lithium-iron(Ferro)-phosphate (LFP) are used. The mass of the battery might reduce the number of allowed passengers if not lightweight chassis constructions are used in the bus production.

The Solaris E12 bus manufactured in Poland can be equipped with battery storage capacities from 80 up to 240 kWh. The resulting charging times of depot charging are in the range from approximately 1.5 to 10 hours depending on charging power range from 20-80 kW and initial state of charge (SoC).

For winter operation but also in tropic climates with very high temperatures significant energy has to be spent on air conditioning of the interior.

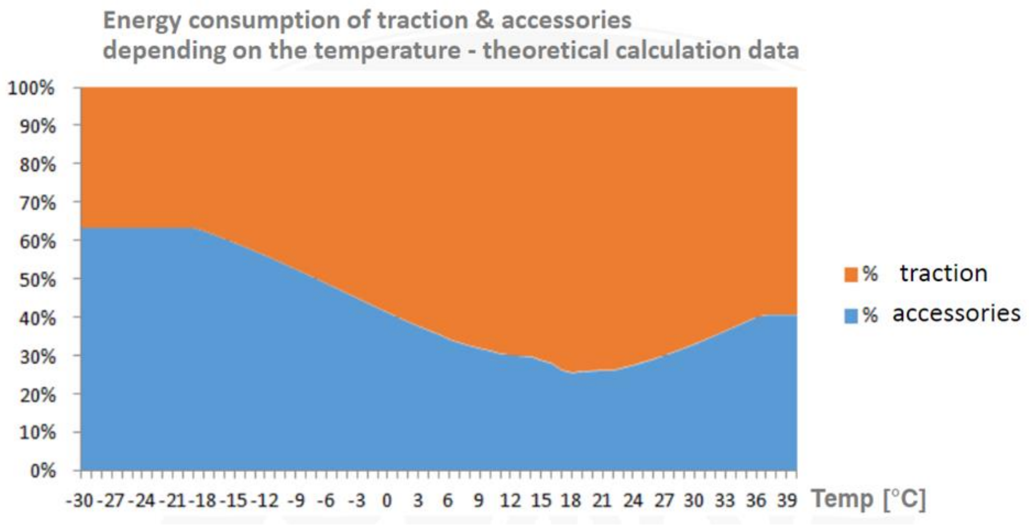


Figure 8 Relative distribution of the energy demand depending on the temperature (Solaris Bus and Coach, 2017) [29]

En-route charging case (aka. Opportunity charging)

For very fast recharging in the range of seconds, the maximum allowable current determines the accumulator size, unless energy is stored intermittently in super-capacitors often called also ultra-capacitors. But since Electric Double-Layer Capacitors

(EDLC) have a very low energy density at high costs, primarily accumulators are used to store a greater amount of energy.

Presently, in the fast evolving markets are offered the following exemplary concepts among others.

Manufacturer	**Energy storage**	**Charging**
Solaris E12 (Poland)	50-125 kWh EDLC	400kW – 5 minutes
CRRC Corp. Ltd (China)	25 kWh EDLC	30 sec
Chariot Motors (Bulgaria)	33 kW ultra-capacitor	340 kW - 30 sec.

There are no big differences between buses with active or passive charging apparatus, there might be slight benefits for infrastructure-based pantographs in terms of investment. The lower the amount of buses operated on a route, the more bus mounted pantographs are suitable. In return, the higher the number of buses the more comes the cost intensive bus mounted pantograph into effect, in the meaning that an infrastructural pantograph might be more cost efficient.

Inductive charging systems are limited by a charging power of 200 kW and have a lower electrical efficiency of 90-95% compared to 95 – 97% for conductive charging. For conductive charging, the weight of the pantograph must be considered with an approximate value of 85 kg (Pihlatie & Paakkinen, 2017) [28].

In-motion charging

For in-motion charging the conductive charging by using wired catenaries is state of the art. The bus has only few accumulators on board guaranteeing some autonomy. This is needed to transfer short stretches without catenaries.

The number of allowed passengers is usually higher compared to buses having larger energy storage. Since energy is not a limiting factor, in trolley buses might be used less efficient but more robust electric engines or less regeneration of braking energy. So, the energy demand might increase to 1.43 kWh/km compared to an exemplary value of 1.28 kWh/km for accumulator powered buses (Misanovic, S. M., Zivenovic, Z. M., and Tica) [25]

But this is seen as preliminary state, since trolley bus technology might improve and lower masses shall result in lower rolling losses. If longer stretches are driven without catenaries off-duty for pull-out/pull-in or dead-head trips, usually air conditioning of the bus interior is not necessary and switched off for energy saving reasons.

2.2.4 Comparison of charging technologies

The qualitative comparison is based on the criteria listed in Table 3.

Table 3 Qualitative comparison of charging technologies

Criterion	Depot Charging	En-Route Charging (Opportunity Charging)	In-Motion Charging (Trolley)
Productive service time	low	lower	highest, some derailments
Investment cost	high	depends on shareability of charging infrastructure and substations	depends whether infra-structure exists
Variable operating cost	lowest	low	low, some charcoal and copper losses
Energy demand	lowest charging losses	higher charging currents with hast charging, ohmic losses	conductive: low losses, in-ductive high losses
Usability of renewables	lowest, if charged in the night	high	high
Life cycle assessment (LCA) vehicle	huge accumulator	smaller accumulator EDLC	small-medium energy storage for some auton-omy
Life cycle assessment (LCA) infrastructure	lowest	medium, many transform-ers	depends on shared usage
Replacement rate Diesel buses	quickly	quick	slowest if no infrastructure exists

For each of the criteria an qualitative evaluation of impact is carried out by assigning a defined number of points to be summed up and are being presented in the multiple criteria decision analysis in Figure 9 in a spider web diagram and in a bar chart of Figure 10.

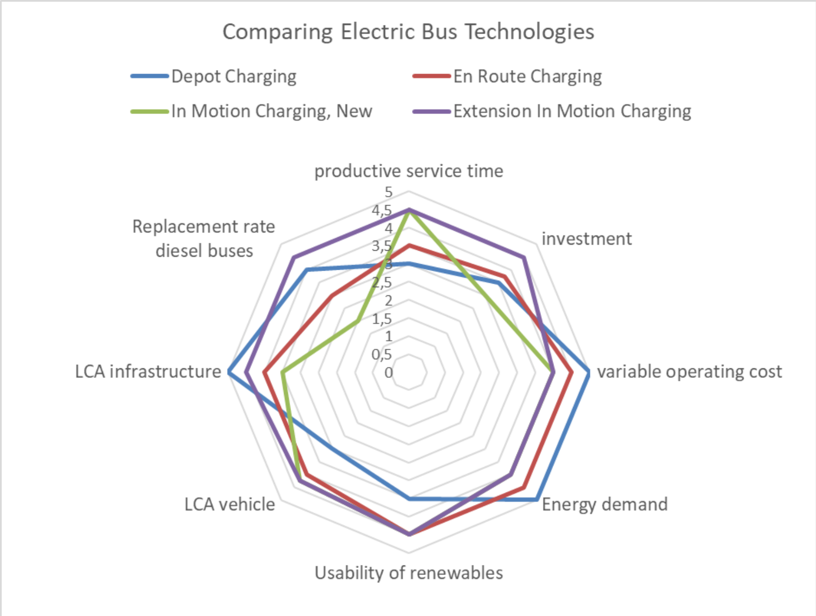


Figure 9 Spider web diagram of compared charging technologies

The results of the multi-criteria decision analysis allow the conclusion that the extension of existing trolley bus networks with dual mode buses is the best solution, followed by depot charging. But there is not much of a difference to en-route charging.

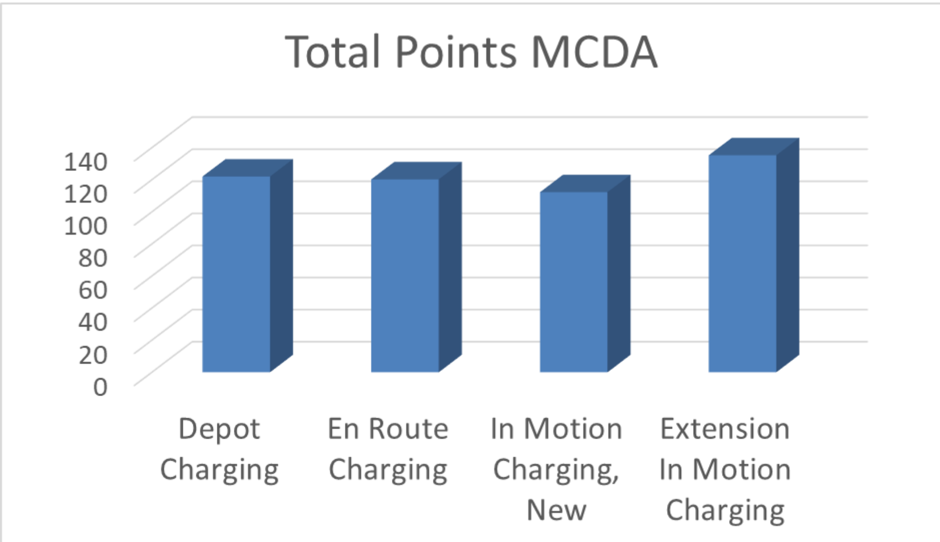


Figure 10 Multi criteria decision analysis chart of compared charging technologies

Semi-quantitative comparison

For a quantitative comparison, several assumptions have to be made. Concerning the power demand per km including heat and charging losses, it must be considered that some heat losses of the battery or electric engines might be regenerated. Thermal conditioning, using heat pumps therefore might deliver a coefficient of performance (COP) of 2 instead of 1 at lowest temperatures.

Concerning the CO_2 equivalents of power generation distinguished between day and night is must be stated that wind and solar energy is dominating the CO2eq value, but in case of sufficient other low CO_2-sources like hydraulic water energy, this effect is the opposite if caloric power plants have to cover increased load during the day, as shown in Figure 11 for a week in May 2019 as received from (Electricity map) [18].

The upper white line represents the carbon intensity in Germany. The fluctuations clearly noticeable result from volatile supply of renewable wind and solar energy throughout the week which has to be compensated by caloric power plants to meet the energy demand. The higher carbon intensity results from energy breakdown share of nearly 50% for fossil fuels in Germany.

The lower blue dotted line represents the carbon intensity of France. In France the carbon intensity is remarkably lower as the energy production is mostly independent from caloric power plants at a rate of nearly 80% CO_2 free nuclear power supply.

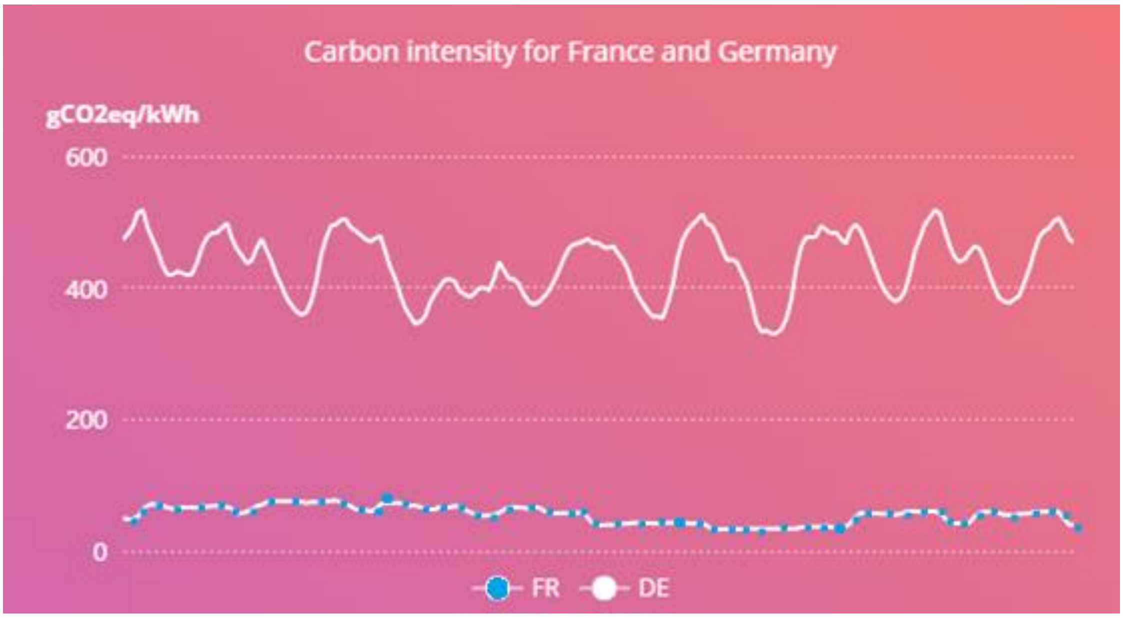


Figure 11 Multi criteria decision analysis chart of compared charging technologies

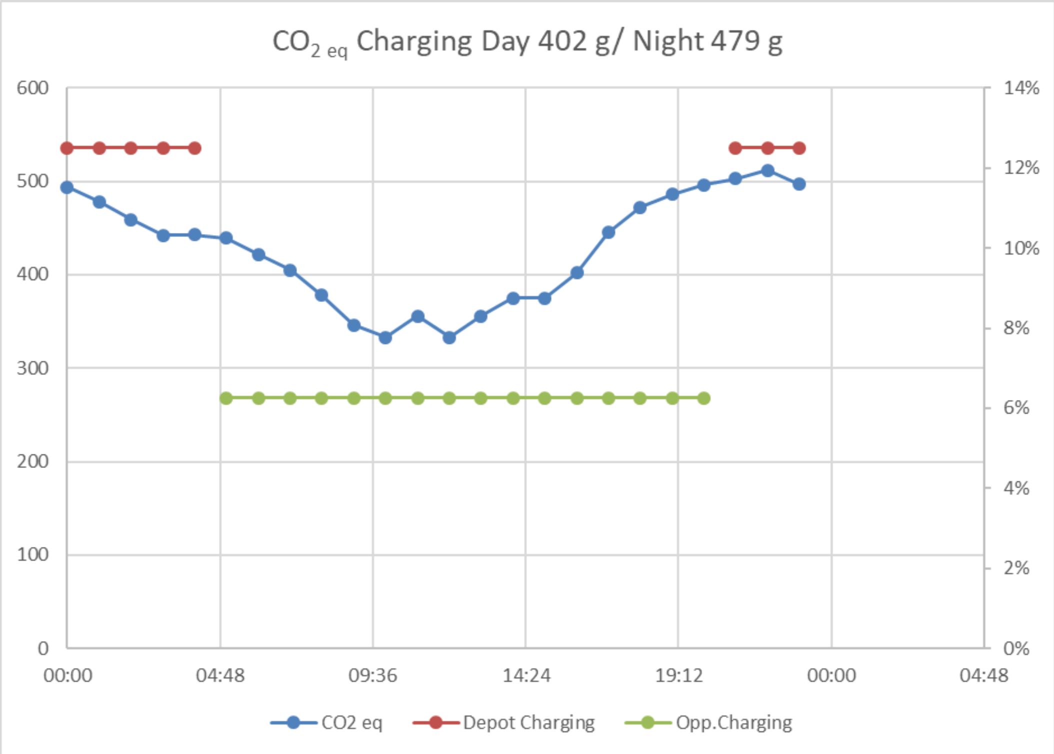


Figure 12 Difference between day and night charging with respect to CO_2 equivalents per kWh on a day in May, 2019. (electricity map)

Figure 12 provides the differences between day and night charging in the case for Germany. It must be noted that this result will differ for every day and depend on the share of wind and solar energy supply. From this example it can be deducted, that given a daily charging of 190 kWh the night charging produces 15 kg more CO_2 per day. Additionally, it must be noted that in times of winter these figures change notably since the solar energy share in winter even during daylight is only 1-2%, so that the carbon intensity for day charging will be higher.

Furtherly it must be considered the grey energy necessary for the production of the energy storage and their related CO_2eq emissions. Romare and Dahllöf (2017) [32] estimate that per kWh Lion (NMC, LFP) battery capacity are being emitted between 145 kg and 195 kg CO2equivalents. For secondary cells (accumulator) values differ for different chemistries. LTO leads with 271 kg CO2/kWh, whereas LFP does have values from 147 to 168 kg/kWh (Naumann, Peters, Weil, and Grundwald (2016)) [26] .

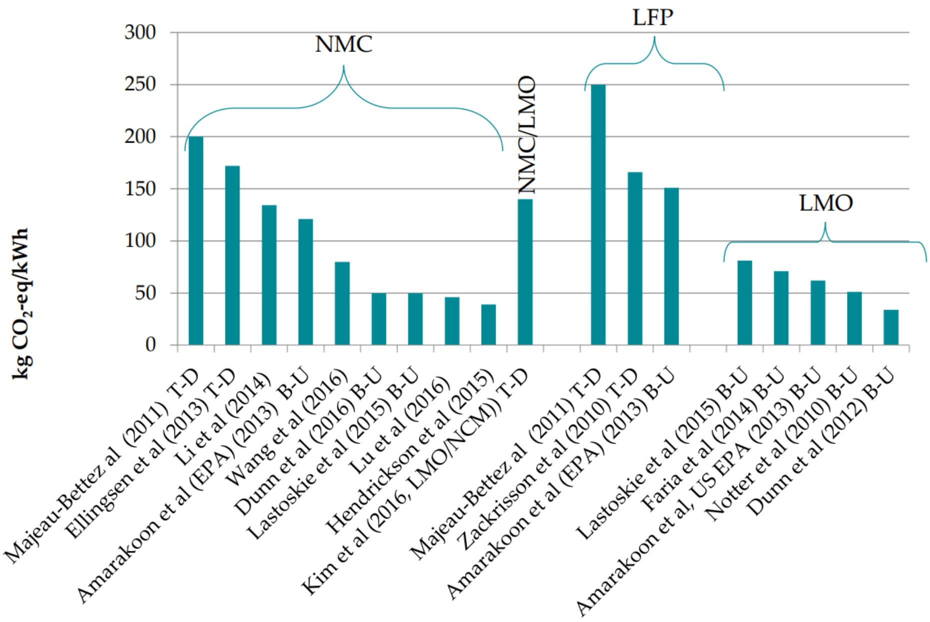


Figure 13 Calculated greenhouse gas emissions for different LCA studies of lithium-ion batteries for light vehicles for the chemistries NMC, NMC/LMO, LFP and LMO. T-D=Top-down approach for manufacturing and B-U is Bottom-Up approach. (Romare and Dahllöf (2017)) [32]

For the application case of using EDLC only, because of this novel technology, it is difficult to find resilient GHW values. For grid coupled EDLC a GHW value of 7 kg CO_2/kWh storage size may be assumed (California Solar Energy Collaborative (CSEC), University of California Davis, 2012) [16]. The cost for EDLC is approximately 10.000 €/kWh.

Source metal structures, charger transformator

The LCA for the transformer was possible using CO2eq for production, use phase and gains from end of life recycling (Hegedic, Opetuk, Dukic, & Draskoivic, 2016) [21]. In this analysis the catenary infrastructure was not taken into account, also not losses of carbon and copper due to wear.

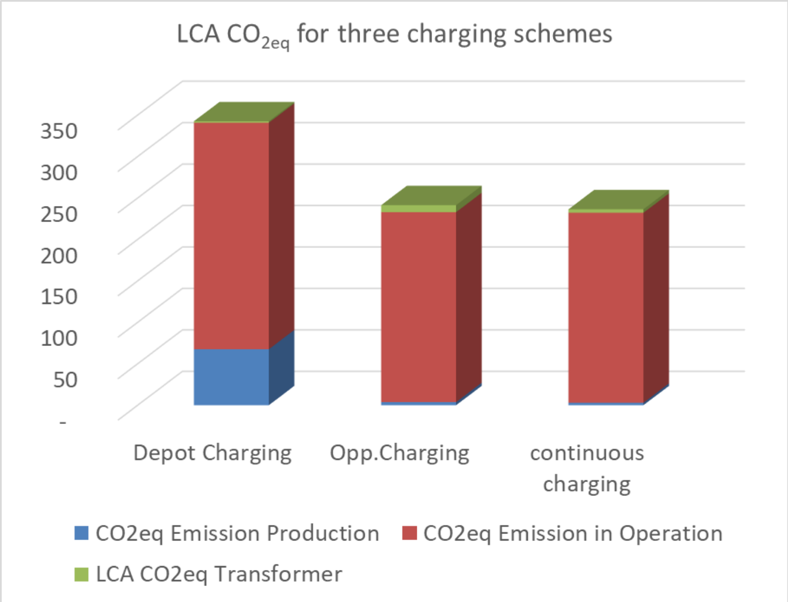


Figure 14 Life cycle analysis $C0_2$eq for depot charging, opportunity charging and continuous charging

Sharing of charging infrastructure

The worst case is if a bus route is equipped with charging stations stand-alone, here it was assumed that two substations having each 500 kW are necessary per route for ultrafast charging.

From the above analysis for a theoretical application case it can be summarized that if a catenary system for trolley buses is not in place, from the holistic view there is no favourite for opportunity or depot charging. If the global warming potential (GWP) is taken into consideration including higher emissions during the night, then opportunity charging is to be favoured. Using more EDLC capacity improves the LCA a small amount, but it should be emphasized the tremendous cost factor of using EDLC.

3 Implementation of the PLATON Toolkit components

In Figure 15 Technology Architecture of the PLATON Toolkitis shown the Technology Architecture between the developed components of the PLATON Toolkit System. The directed arcs between the green marked tool components represent flows of data objects from their source to their destination including defined categories and formats. The distinguished planning levels are indicated as the *strategic corporate planning level* and the *transport operation planning level*. Decision support will be provided in form of generated reports that comprise the most important output for strategic decisions such as TCO projection of the bus fleet, electrification priority of routes, procurement recommendation based on the configuration of vehicle, batteries and charging infrastructure.

More specific planning support is provided to the transport operations level such as scheduling for electric buses, opportunity charging locations or potential transit network adaptations with regard to the existing power grid under consideration of the transit demand. The architecture reveals the data flow, interfaces and sources of data for the toolkit system which is developed to the extent of the shown process diagram.

For the further analysis it is assumed that for the purpose of decision support the legislative/governmental level and the strategic corporate planning level will be considered as combined. This is because of the shareholder structure in most public transport agencies of Europe and overseas. As a rule, it can be assumed that the public transport operator of a territorial community is owned with the majority of shares by the urban or regional administrative body that itself is authorized by the political legislative body. Therefore, if the political will of bus fleet electrification is adopted by the legislation, the task of execution is in the hands of the government who itself will move forward resolutions in the corporate shareholder's assembly to be executed by the corporate management of the public transport agency. Following this reasoning it is justified to provide economical, technical and operational decision support only to the strategic corporate planning level in the form of the CEO and the management board.

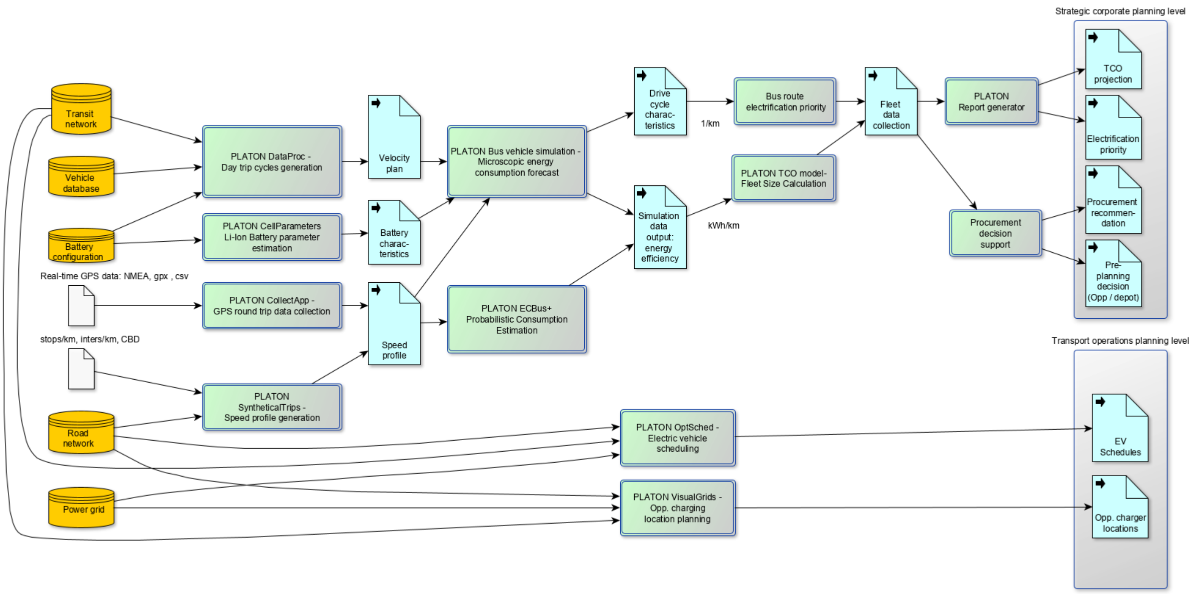


Figure 15 Technology Architecture of the PLATON Toolkit

In the following section the major components of the PLATON Toolkit are described as subsystems regarding their required input data as well as their produced output information as elements of the toolkit framework.

3.1 Required data input

Nearly all of the tool components rely on geographically referenced data that represent the existing transit network covering the area, serviced by a particular transit agency. Ideally, the mapping data is available in an exchange format that enables seamless integration into each of the planning tools. A standardized data interface enables not only the exchange between planning tools as well as the application of the complete tool set in an arbitrary transit service area. The required basic layers of input data comprise the transit network including depot, stop and terminal locations, bus routes, frequencies of bus departures during the peak traffic period as shown exemplary in Table 4.

The transit network can be provided as *General Transit Feed Specification (GTFS)* [0] or in form of available GIS-shapes. A feasible source for this information may also be utilized from the *OpenStreetMap* [2] contributors for transit network, road network and power grid by referencing the information source. A further useable source for transit network and timetable data is the *VDV 452 (Interface Network Timetable*) [3]. The workflow includes capturing geographic data on shapes of route segments, stops, and assigned trips with stop times for the given timetable of bus services.

Table 4 Example of tabular data in Comma Separated Value (CSV) file stops.txt with tabular organized data like geometries, sequences, references, timetable and network data.

```
route id,trip id,parent station,stop id,stop sequence,stop lon,stop lat,x,y
R53,T2822001,S5705901,S5705902,7,11.561104,52.088903,1286976.2,6816216.2
R52,T1932001,S5000701,S5000703,22,11.628128,52.108392,1294437.3,6819747.9
R71,T2377001,S2000201,S2000202,6,11.574198,52.149498,1288433.8,6827201.9
R73,T2636001,S2201,S2207,5,11.639302,52.136404,1295681.2,6824826.7
R55,T2044001,S5500301,S5500301,4,11.586701,52.113503,1289825.7,6820674.3
R59,T2929001,S5901101,S5901102,8,11.620094,52.122899,1293542.9,6822377.7
R55,T2043001,S6100301,S6100302,4,11.594006,52.119298,1290638.8,6821724.9
```

Geometric route conditions are an integral part of the GTFS data feed that is provided either by the public transport agency or may be downloaded from transit associations. The data feed contains among other data information on route shapes, stop locations, trips, and stop times. Based on these basic data, and in consideration of the road network from open sources such as OpenStreetMap, the speed profile data for a given bus route can be generated without having collected real time data of longitudinal acceleration movements in advance.

3.2 Component DataProc

The generation of realistic speed profiles is necessary for the task of energy consumption forecast by using the *ECBus+* and *BusVehicleSimulation* components. The speed profile is more realistic if actual geometric conditions of the route and road network properties are taken into account. The *DataProc* tool utilizes the prepared data sources to generate trip cycles of bus movements either for a single trip or return trip between terminal stops as well as for full day trip cycles on a second by second basis. The output data is provided in form of a velocity plan to the bus vehicle simulation tool component as shown in Figure 16. The velocity plan is the time-variant reference variable as the course of set points for the control of vehicle velocity by the simulated controller that represents the autonomous drive control of the vehicle simulation [13].

The *DataProc* component was developed to solve the task of speed profile generation as an integral part of the PLATON Toolkit to complement the created existing toolkit components and to connect to these by the defined data/file interface. The generation of speed profile data is achieved with numerical integration to obtain vehicle speeds and travelled distances. Special cases of close distances between stops exist and lead to speed profile fragments in which the maximum speed is not reached. For example, if the distance between stops is lower than the distance travelled during acceleration to maximum speed and the distance travelled during deceleration to zero velocity, the resulting speed profile is abridged accordingly.

The output files of the tool component *DataProc* include the generated speed profile that are compatible for input to *ECBus+* for further processing and energy consumption forecast.

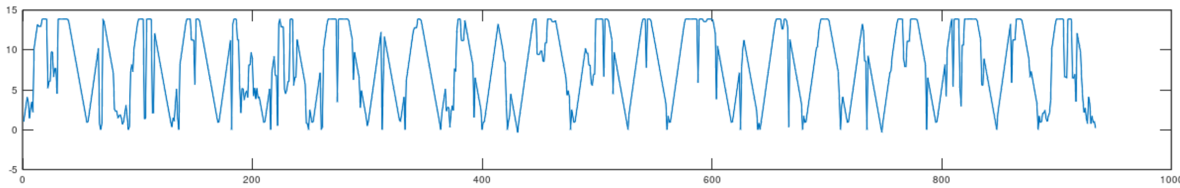


Figure 16 Realistic velocity plan for a vehicle cycle including halts at intersections and bus stops

3.3 Component CellParameters

The energy system implemented on E-buses in PLATON is Lithium-ion battery package. One of the key challenges in electrification of public transportation is the selection of battery types and capacities, which can be determined by a battery model developed in SIMBA# [14]. The model is designed based on the third-order equivalent circuit, which is shown in Figure 17. The adopted battery cell is a Lithium-iron-phosphate (LFP) cell, with parameters shown in Table 5.

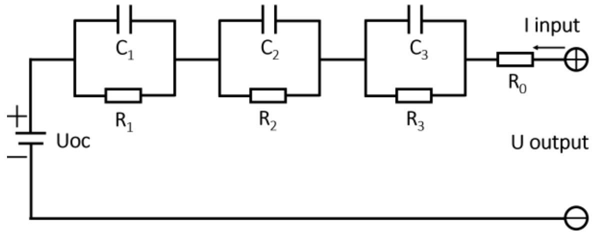


Figure 17 Third-order equivalent circuit

The accuracy of values of circuit components can determine directly the final simulation result of this battery model. Therefore, parameter estimation plays a vital role in battery modelling.

Table 5 Parameter of LFP battery cell

Manufacturer	A123 Systems®
Model	ANR26650M1-B
Nominal Voltage	2500 mAh
Rated Capacity	3.3 V

As described by Yan et al. [9], the output voltage can be represented by equation (4), where U_{oc} is the open-circuit voltage of the battery, $U_1 \sim U_3$ are respectively the voltages of these three RC branches.

$$U_{output} = U_{oc} + IR_0 + U_1 + U_2 + U_3 \tag{4}$$

The terminal voltage of this LFP battery cell was measured at the room temperature with the instrument c't-Lab, which can collect data at a high frequency then transfer the values to the computer via a COM port, the instrumental set-up is shown in Figure 18.

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Figure 18 Instrumental set-up for voltage measurement

The software LabVIEW® is used to generate current pulses to control the charging or discharging process. To simplify measurement, the battery cell is discharged from a fully charged state to a fully-discharged state with 10 times, as presented in Figure 19. In other words, the SOC decreases 0.1C at each discharging pulse from 100% to 0%. Therefore, the discharging current is set to be 0.5C, the period for discharging is 12 min, and the recovery time is 1 h, which is long enough for the battery to cool down and reach a stable state, which is marked as segment b ~ c in Figure 20.

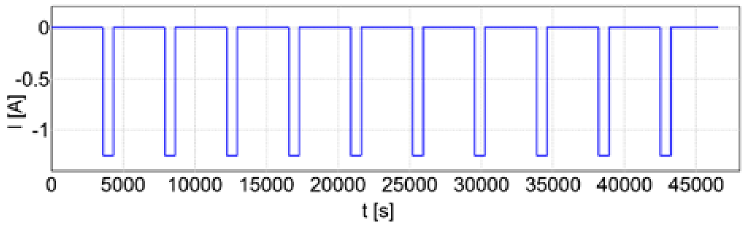

Figure 19 Discharging current pulses

When discharging current equals zero, SOC is viewed as a stable value, which is suitable for parameter estimation. Segment b ~ c describes the hysteresis response (i.e. zero-input state response) of the battery, whose output voltage can be furtherly represented by equation (5). The time constant of $\tau = RC$ means the recovery time of RC branches, with initial voltages at point b represented respectively by $U_1(0) \sim U_3(0)$.

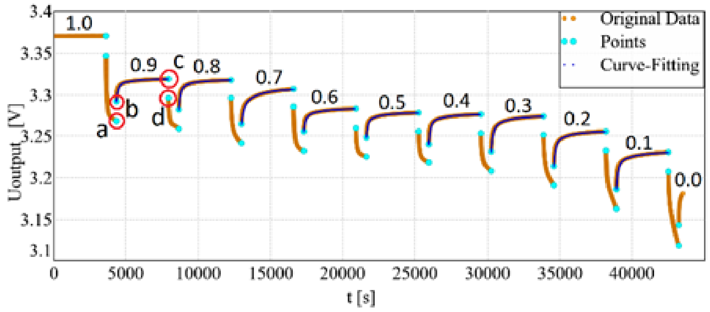

Figure 20 Measurement and estimation data of output voltage

$$U_{output}(t) = U_{oc} + U_1(0)e^{-\frac{t}{\tau 1}} + U_2(0)e^{-\frac{t}{\tau 2}} + U_3(0)e^{-\frac{t}{\tau 3}} \tag{5}$$

At each steady state, the final voltage value at point c is extracted as the open-circuit voltage (i.e. $U_{oc} = U_c$). Segment a ~ b and c ~ d describe the instantaneous response of the battery, which is caused by R_0. Therefore, the average value of internal resistance for each SOC can be calculated directly with the voltage difference in equation (6).

$$R_0 = \left(\frac{\Delta U_{ab}}{I} + \frac{\Delta U_{cd}}{I}\right) \div 2 \tag{6}$$

After obtainment of U_{oc}, (2) can be transformed into equation (7), which is obviously a curve-fitting problem with a triple exponential function, where $y = U_{output} - U_{oc}$.

$$y(x) = be^{px} + ce^{qx} + de^{rx} \tag{7}$$

After a long recovery time, the polarization voltage can be neglected. As a result, discharging periods are viewed as zero state responses. And for segment a ~ b, at such a short instant, the polarization voltage has nearly no change. With t_k representing the discharging intervals, $R_1 \sim R_3$ and $C_1 \sim C_3$ can be furtherly obtained with equation (8).

$$\begin{cases} U_1(0) = IR_1\left(1 - e^{-\frac{t_k}{\tau 1}}\right). \\ U_2(0) = IR_2\left(1 - e^{-\frac{t_k}{\tau 2}}\right). \\ U_3(0) = IR_3\left(1 - e^{-\frac{t_k}{\tau 3}}\right). \end{cases} \tag{8}$$

The simulation result of the model with 3 RC branches is shown in Figure 21. As is displayed, the simulation data created by the exponential regression algorithm can fit the measurement data well.

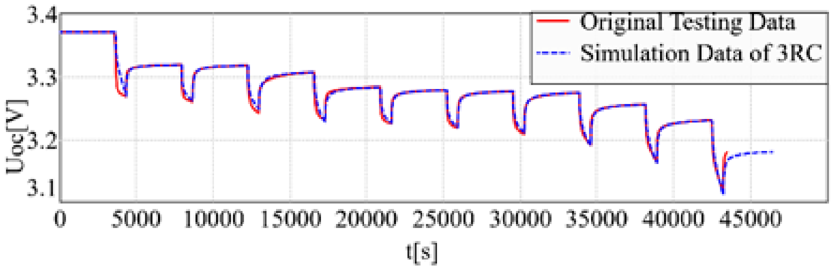

Figure 21 Simulation result of 3 RC branches

After comparison between these two curves, a diagram of error is generated as Figure 22. Obviously, errors exist mainly in discharging periods, when SOC is always changing and no steady values of resistances and capacitances can be determined. Before voltage measurements, the battery cell has been fully cooled down, so there is no sufficient recovery data for parameter estimation. It is the reason that for the first discharging pulse, the error is larger.

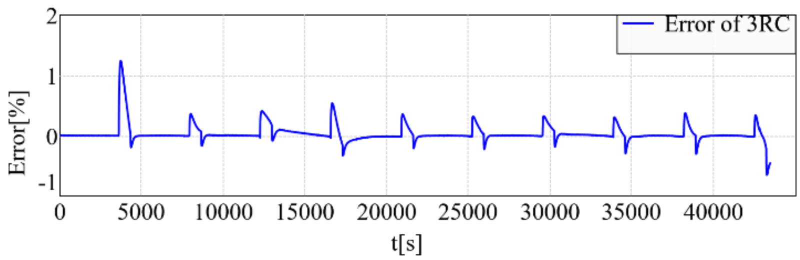

Figure 22 Simulation error of 3 RC branches

After computation, the residual error is 1.98 mV and the relative error is 0.06099%. In order to validate the practicability of the 2+ exponential regression algorithm for parameter estimation, the periods before SOC = 90% and after SOC = 10% are removed. Therefore, the updated mean residual error is 1.60 mV together with the relative error of 0.04927%.

3.4 Component CollectApp

The *CollectApp* application includes a GPS data logger implemented for use on Android[TM] smartphones. Real-time data of position, heading and acceleration is collected during one or more consecutive transit trips. The collected data of real trips that were taken in buses during duty cycles are stored in GPS-files of different formats. Well known formats are NMEA (National Marine Electronics Association) and GPX (GPS Exchange Format). Any of the named text based formats can be processed by other components of the PLATON Toolkit.

In addition, real-time data of buses can be acquired using a hardware logger, developed to collect GNSS data with higher resolution than 1 Hz that is used by Smartphone GPS only. The PLATON *HiResLog* enables to acquire positioning data up to 20 Hz. Using the high resolution positioning data enables to aggregate precise velocity profiles for bus vehicles with exactly measured acceleration and deceleration values for longitudinal vehicle movements.

The collected data is shown in Figure 23 and contains the timestamp, geographical position in WGS84 coordinates, distance to preceding track point in meters , time difference in milliseconds, instantaneous velocity in meters per second, instantaneous acceleration in meters per square second, current barometric pressure, and calculated elevation difference relative to starting track point. The data/file structure is seamlessly enterable to speed profile generation tool *SyntheticalTrips* described in the following paragraph as well as to *DataProc* tool describe above.

GPSlog3.txt

```
"Fri Nov 09 14:12:09 MEZ 2018",52.1407207,11.6564318,4252597.14,1541769129050,0,1.56,1009.79,-3.
"Fri Nov 09 14:12:10 MEZ 2018",52.1407179,11.6564413,0.72,1001,0.72,1.96,1009.87,-3.2
"Fri Nov 09 14:12:11 MEZ 2018",52.1407125,11.656466,1.79,1000,1.79,1.63,1009.81,-3.69
"Fri Nov 09 14:12:12 MEZ 2018",52.1407051,11.6564979,2.34,1000,2.34,1.21,1009.74,-3.45
"Fri Nov 09 14:12:13 MEZ 2018",52.1406903,11.6565356,3.06,1000,3.06,1.53,1009.83,-3.36
"Fri Nov 09 14:12:14 MEZ 2018",52.1406731,11.6565739,3.25,1000,3.25,1.57,1009.83,-3.28
"Fri Nov 09 14:12:15 MEZ 2018",52.1406539,11.6566197,3.8,1000,3.8,1.87,1009.92,-3.77
"Fri Nov 09 14:12:16 MEZ 2018",52.1406371,11.6566509,2.83,1001,2.83,1.5,1009.78,-4.35
"Fri Nov 09 14:12:17 MEZ 2018",52.1406181,11.6566776,2.8,1000,2.8,1.44,1009.87,-3.69
"Fri Nov 09 14:12:18 MEZ 2018",52.1406045,11.6567044,2.38,1000,2.38,1.35,1009.82,-3.45
```

Figure 23 Real-time data interface provided by CollectApp tool component

3.5 Component SyntheticalTrips

The *SyntheticalTrips* component comprises a simulation model for the automatic generation of typical dynamic motion sequences of bus vehicles in urban public transport. Typical motion sequences include traffic-related starting and braking processes in connection with the traffic flow, turning processes at unsignalled and signalled junctions and the operation of bus stops for passenger exchange.

The speed profiles represent the most realistic vehicle behaviour possible and are to be used for estimating energy consumption with an existing vehicle model for an electric bus and with the processing program provided by a project partner. For the generation of the speed profiles, input data such as the maximum acceleration and braking acceleration, the permissible maximum speed, the traffic density, the density of intersections in the traffic network and the density of stops are used as variables.

3.6 Component BusVehicleSimulation

The vehicle simulation component is a sub-microscopic tool component. In contrast to car following oriented microscopic simulation it is developed to model realistic vehicle movements using various individual parameters including the rolling resistance on road surfaces, grade angle of the road segment, and a tractive force vehicle model, following Sun et al. [4] in which the tractive force F_{Tr} equals the resistance forces like rolling resistance F_R due to tire and road resistance, drag resistance F_W due to air and vehicle interaction, grade resistance F_G due to the grades of the road, and acceleration resistance F_A due to accelerate the vehicle mass.

$$F_T = F_R + F_W + F_G + F_A \tag{9}$$

or

$$F_T = K_R \cdot m \cdot \cos(\theta) + K_W \cdot A \cdot v^2 + m \cdot \sin(\theta) + m \cdot \frac{a}{g} \tag{10}$$

with rolling resistance coefficient $K_{R,}$ vehicle weight m, road angle θ in radians, wind resistance coefficient K_C, vehicle frontal area A, vehicle speed v, vehicle acceleration a and gravitational constant g.

The vehicle simulation allows a full-day revenue service cycle as the basic transport task:

a) Pull-out from depot to the terminal stop of the transit route on the shortest path,

b) Round trip revenue route service between terminal stops on the transit route including opportunity charging at one of the terminal stops, and

c) Pull-in from terminal stop to depot for servicing and overnight charging.

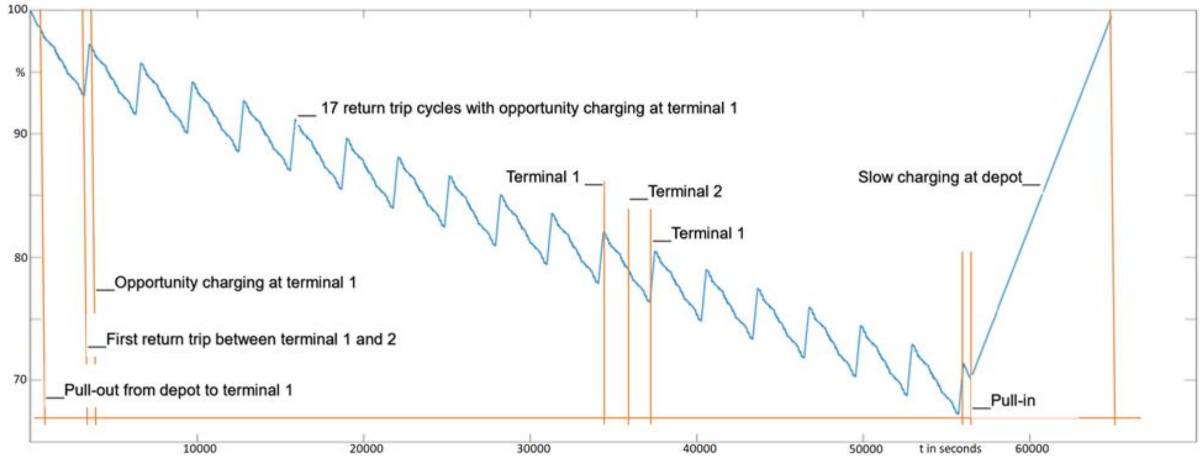

Figure 24 Simulated State of Charge involving recharging for full-day trip cycles including depot rides.

The vehicle driving cycle is simulated by means of a closed-loop discrete system of the vehicle model and a controller in a feedback loop. A proportional integral (PI)-controller is used to simulate the acceleration and deceleration actions of the driver. The output of the simulation is shown in Figure 24. The velocity profile is used as the time-variant reference variable that is obtained either from the acquired output of the *CollectApp* tool component or from the generated speed profile output of the *ECBus+* tool component.

3.7 Component ECBus+

The complete *ECBus+* tool component includes: the software *ECBus* and the procedure *EC-compare* which is a comparative method for evaluating energy consumption for electric buses based on data for diesel buses and probabilistic approach to determine the energy consumption value. In the first step the bus power consumption is estimated using the *ECBus* software. In the second step the *EC-compare* procedure is applied for a local case by using the determined power consumption values for the bus with the probabilistic representation of the road and traffic conditions of the route cycle. The probabilistic approach, developed by Algin [5] requires the user to responsibly choose a probability to attain a value of energy consumption not to be less than the value accepted for the calculated one.

3.8 Component TCOModel

The component of Total Cost of Ownership (TCO) analysis is to support decision making of the transit agency management board at the strategic planning level. This component helps to investigate all costs of the ownership of the bus fleet during its life cycle. The underlying TCO model of the tool component was derived to reflect consumer oriented and society oriented approaches as suggested in [6], [7], and [8], whereas the consumer oriented approach reflects the life cycle costs of the vehicle without externalities and the society oriented approach includes externalities, such as environmental costs representing air pollutant and GHG emissions, noise, and marginal well-to-tank costs. The method implemented in the tool is distinguished into both a static and a dynamic approach. The static model takes into account the costs categories such as capital costs of buses and chargers procurement by depreciation costs, maintenance costs, mid-term costs, energy costs, and financing costs like interest expenses and repayment instalments. The dynamic model is based upon the cost categories of the static model and takes into consideration time relevant staggering procurement of vehicles, batteries and infrastructure, different financing models including funding by subsidies, loans or leasing models. Other time invariants include assumptions on future vehicle, battery, and energy prices.

The implementation of the dynamic-societal TCO model as shown in Figure 25, including the structured computation process, forms the software core of the *TCOModel* tool component that is parametrized by various input variables of technical, economic, operational, and variables of externalities to describe the specific conditions in the particular application case.

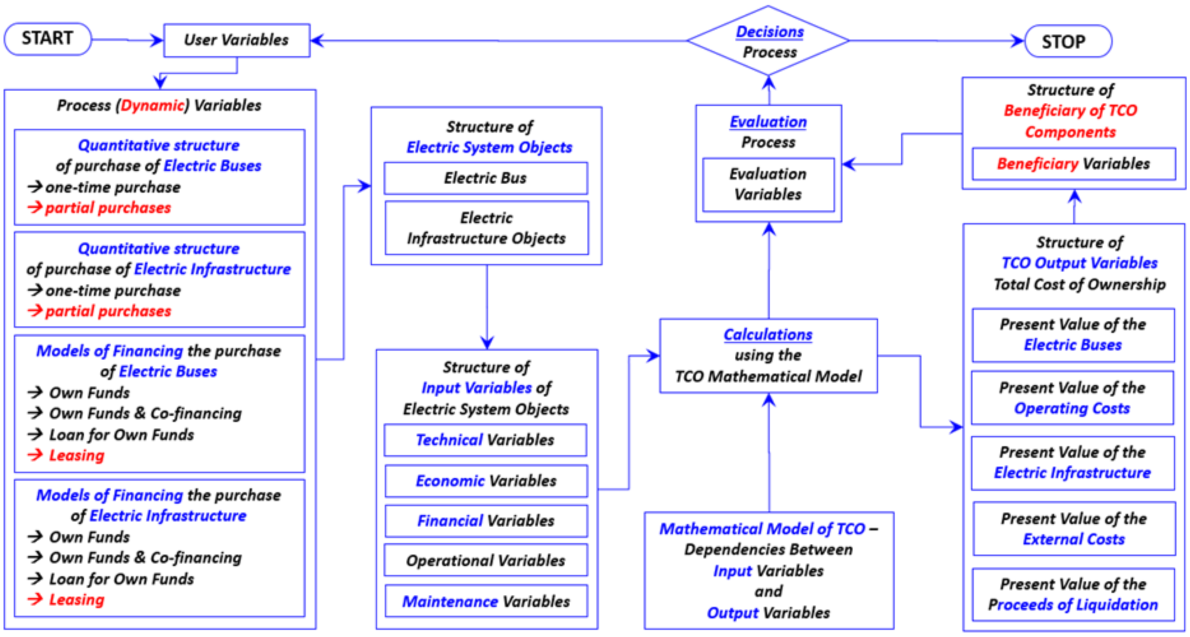

Figure 25 Structured process of TCO computation using the dynamic-societal model from [11]

3.9 Component OptimSched

The tool component for optimization and scheduling is denoted as *OptimSched*. It is comprised of different implementations of optimization problems. The optimization problems are formulated and analysed for a given set of public transport routes intended for the introduction of electric buses. In the first problem, denoted as Opt, fast-charging technology is assumed. This problem is to determine a fleet of electric buses, places for charging stations and transformers, assignment of charging stations to the selected places, assignment of charging stations to the transformers and assignment of charging stations to the routes such that all the electric buses can feasibly drive, the required traffic (inter-bus) interval is maintained, and the output power of any transformer is not exceeded. The objective is to maximize the total value, provided that the total capital cost and the total operating, depreciation and energy cost do not exceed their upper bounds. The total passenger capacity of the replaced conventional vehicles can be considered as the value to be maximized.

In the second problem, denoted as *DepOpt*, a slow-charging technology is assumed. This problem is to determine the required electric power supplied to the depot by the city power grid, the type and the number of charging stations of this type in the depot, types of e-bus batteries and charging times of each e-bus while it is in the depot such that the total daily cost of the equipment and the consumed energy is minimized, provided that the arrival and departure times of e-buses to/from the depot, the dynamic upper bound on the supplied power and functions of charge and discharge of the batteries are addressed.

The third problem, denoted as *OptSched*, is to determine a balanced route timetable such that the same average traffic interval of all public vehicles of the same route is maintained and departures of public vehicles of the same passenger capacity assigned to the same route are distributed as smoothly as possible over departures of all public vehicles in the most representative time period.

Input data for all distinct software parts are defined in a well-described file interface that is expected to be prepared before using the optimization softwares by transportation engineering experts.

3.10 Component VisualGrids

The *VisualGrids* component integrates a number of data sources from outputs of tool resources to incorporate dependencies of different domains for decision support at the transport operations planning level such as the opportunity charger location planning. For the planning of opportunity charging stations it is required to take into account the medium power grid along with the road network and the transit network in a combined approach. Therefore, a visual representation of the considered networks like shown in Figure 26 Interface of VisualGridsis needed to describe the geometric relationships of transit stop locations, power transformer and substations along a 10-30 kV power line, and the distances of stop locations along the bus route, and between stops and power lines. With *VisualGrids* it is possible to visualize bus routes including stop locations and the power line including substations by queries of the online databases of Open-StreetMap [2]. The road distances from transit stops locations to existing or planned power transformer stations are measured by editable segments within the underlying road map. Based on available data sources an approximated TCO projection can also be conducted for a rough estimation of expected operational costs.

The inputs of *VisualGrids* are transit network, road network and power grid. After the processing of related data, this component can generate appropriate opportunity charging locations on the open street map (OSM). As shown in Figure 1, *VisualGrids* is a part of PLATON Toolkit. After the input of a specific route number (e.g. 73), the interface will present the round trips of this bus route, which are marked by blue lines with bus stops. All related coordinates of every location point are acquired by means of API provided by OSM in the following form, shown in Table 6.

Table 6 API of OSM parameters for queries

```
[out:json][timeout:25];
// gather results
(
  // query part for: “ref=73”
  node["ref"="73"]({{bbox}});
  way["ref"="73"]({{bbox}});
  relation["ref"="73"]({{bbox}});
);
// print results
out body;
>;
out skel qt;
```

The [“ref”= “73”] is used to define bus route of No. 73, and the {{bbox}} has to be set to be the border of the visual interface to request for data from the API.

Then by clicking the first button on the right side to show the power substations in the visual area, which are displayed by orange markers in Figure 26. This is accomplished by replacing the tags to ["power"="substation"]. The distance between each power sub-station to route points could be further measured and analyzed to find appropriate sites for charging stations and to consider suitable charging standards. The function of dis-tance measurement can be activated by the left button with “arrow” mark. A possible path with distance shown is presented by black lines on the map connecting a power substation and the bus route for an example. This distance measurement function can be proceeded manually according to practical requirements.

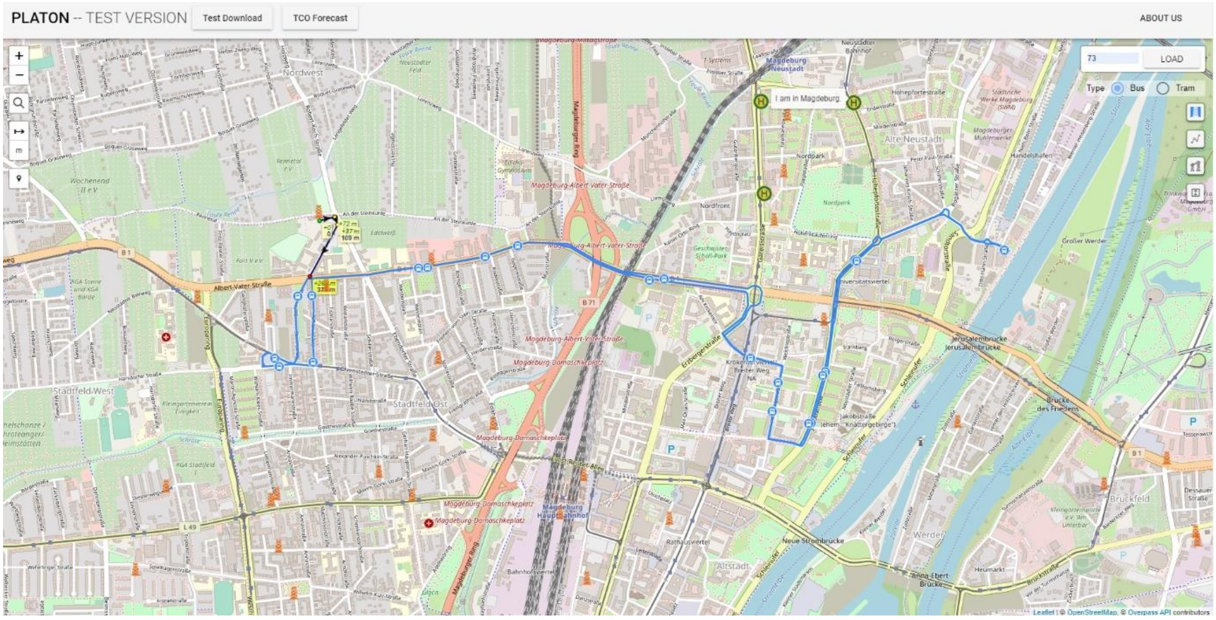

Figure 26 Interface of VisualGrids

If the bus routes are not accurate enough, they can be further edited and adjusted by the function of showing editable points. As shown in Figure 27, the red circles can be dragged to adjust the routes according to the actual situation.

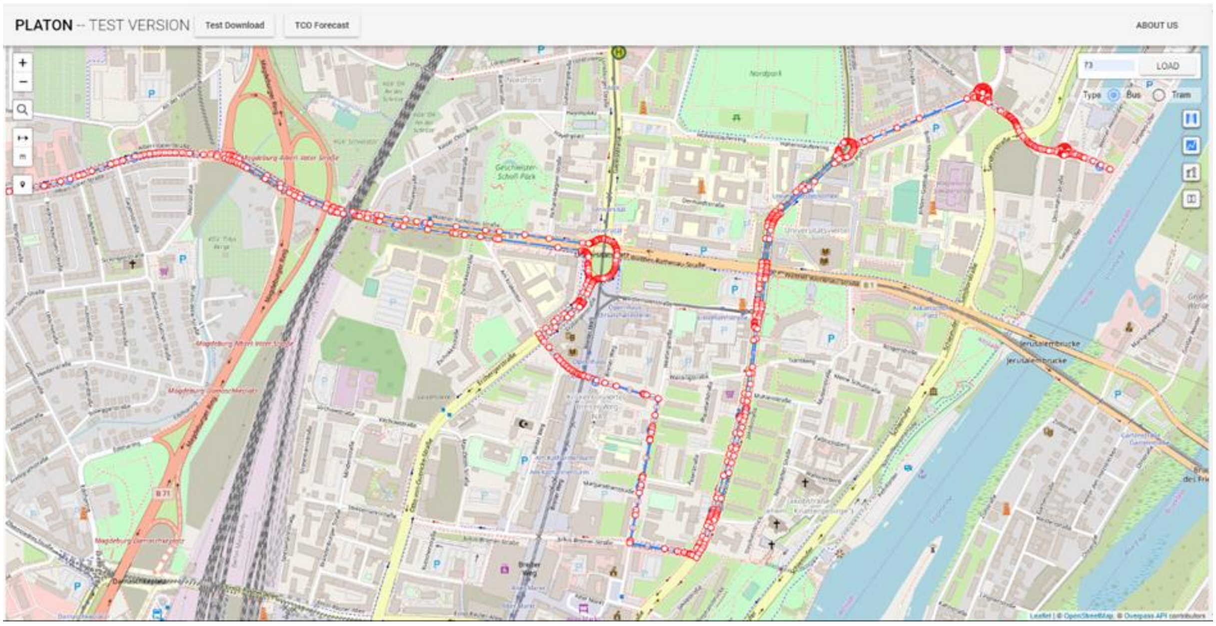

Figure 27 Showing editable points of bus routes

3.11 Components Report generator and Procurement decision support

For the practical realization of the economical, technical and operational decision support a concise reporting document is generated to contain the basic results of total cost of ownership projection for the mid-term financial planning horizon, further a proposal for electrification priority of bus routes based on calculated kinetic intensity, a procurement recommendation based on the bus vehicle market research and battery configuration with opportunity or slow depot charging option. The concise reporting document is expected to provide and easy-to follow decision support by collection of output data from different tool components of the Technology architecture, as shown in Figure 15.

Similar to the report generator the *Procurement decision support* component serves to summarize the configurations of vehicle and charging infrastructure that have been analysed be the toolkit for the given deployment case under consideration of the respectively existing markets for buses, batteries and charging facilities. The tool component is provided to facilitate the tendering process by definition of operational and technical specifications that meet the requirements of each considered deployment case.

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